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APPLICATION OF REMOTE SENSING TO REAL-TIME MANAGEMENT OF MARINE RESOURCES: TODAY AND TOMORROW

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Today's Use of Remote Sensing in Real-Time Management of Marine Resources - Since 1992 the National Marine Fisheries Service, NOAA has used sea surface temperature (SST) imagery from NOAA polar-orbiting weather satellites provided by the CoastWatch program, along with biological observations, to determine the need to modify trawling gear rules under the Endangered Species Act for sea turtle conservation during summer flounder fishing season. An intensive trawl fishery for summer flounder off Virginia and North Carolina takes place during fall and winter on the continental shelf from Chesapeake Bay south to Cape Hatteras, NC. This narrow continental shelf is occupied in the same season by endangered and threatened sea turtles. The increase in fishery-sea turtle interactions occurs in waters with temperatures >11°C. Water masses near Cape Hatteras, NC are spatially and temporally dynamic and NOAA-NMFS fishery managers need near real-time environmental monitoring capabilities to protect sea turtles, while allowing the flounder fishery to continue using area-appropriate gear limitations.

Tomorrow's Use of Remote Sensing in Real-Time Management of Marine Resources - *Gymnodinium breve* red tide blooms occur in the Gulf of Mexico almost every year and cause severe natural resource, public health and economic impacts. As a result of widespread and prolonged blooms (from Texas to Florida) during 1996, *G. breve* caused fish kills, closures of shellfish harvesting areas, respiratory irritation to beach goers and economic losses to local communities that depend on tourism, recreational activities, and fisheries. The deaths of approximately 150 endangered manatees in southwest Florida waters at that time were attributed to *G. breve* exposure. Typically blooms start offshore in late summer and fall in conjunction with intrusions of Gulf Loop Current water onto the outer continental shelf. Following cross-shelf transport, largely influenced by winds, and wind-induced upwelling or downwelling, *G. breve* cells concentrate and grow near the midshelf front. If cross-shelf transport mechanisms persist, blooms concentrate in nearshore waters where winds and alongshore currents govern their movement

Efforts are underway to integrate a variety of remote sensing capabilities and evaluate the sensitivity, reliability and consistency of their products to detect fronts, water masses, surface currents, high biomass areas and other oceanic conditions conducive to the transport of *G. breve* blooms. Combined with traditional observational systems these help to establish a "nowcast system" for locating *G. breve* blooms and, ultimately, develop the critical parameters needed to short-term forecast or predict bloom transport into coastal waters. Early warnings issued to coastal communities and resource managers would provide an opportunity for appropriate mitigation activities.

I. Today: Introduction

Many of the human-associated mortalities to all five species of protected sea turtles in the United States Atlantic and Gulf of Mexico waters have been attributed to fishing activities (Magnuson et al. 1990). Sea turtle distribution on the Atlantic coast of the U.S. includes an annual pattern of northward dispersal to New York waters or beyond in spring-summer and a southward migration in autumn-winter to warmer continental shelf waters south of Cape Hatteras, NC. From the Chesapeake Bay mouth to Cape Hatteras, NC the continental shelf narrows appreciably. South of Cape Hatteras it broadens again forming a constricting transit corridor. Sea turtles and several migrating finfish

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species (such as summer flounder, weakfish, and Atlantic menhaden) concurrently traverse this narrow shelf area and are subject to heavy fishing pressure as they move south in late autumn-winter. A trawl fishery for summer flounder is very intense in the shelf waters off southern Virginia and North Carolina between October and April. Trawling activity is focused in the nearshore waters early in the fishing season, but as water temperatures cool on the shelf, the primary summer flounder fishing grounds shift to the deeper (warmer) shelf and canyon areas, principally north of Cape Hatteras. Annually, the distribution of finfish and sea turtles, mediated by the declining seasonal temperatures and the location of vessels in the summer flounder trawl fishery, result in fishery-turtle interaction with "takes" (deaths) of sea turtles occurring in trawls. This pattern of interaction is demonstrated by the annual coincidental stranding of relatively large numbers of dead sea turtles on the beaches of northern North Carolina during the trawl fishery in late autumn and early winter (Epperly et al. 1995). In 1991 National Marine Fisheries Service and the North Carolina Division of Marine Fisheries developed a cooperative study plan to monitor the summer flounder trawl fishery and sea turtle movements during the 1991-92 season. The objectives to of the study were of provide protection to the sea turtles and maintain a flounder trawl fishery in the area. Program activities included 1) aerial surveys for position-distribution of the trawl fleet and sea turtle presence-incidence 2) at-sea observers on trawlers for sea turtle catch per unit effort (CPUE) and turtle species-condition data, and 3) examination SST data. It led to a much improved understanding of oceanic and weather factors which bear on the issue of sea turtle and finfish distribution in the vicinity of Cape Hatteras. Study methodologies are provided in some detail by Chester et al. (1994) and Epperly et al. (1995) along with summary satellite imagery.

II. Today: Methods, Results & Discussion

Seawater surface temperature imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor on NOAA-11 polar orbiting satellite was obtained in near real-time (6-12 hours after satellite pass) via the NOAA CoastWatch node at NMFS-Beaufort Laboratory (Chester and Wolfe 1990). Wind speed at Cape Hatteras was provided by the NOAA-National Weather Service. Sea turtle sightings from aerial survey and on-board observations were overlain with the SST data and related to fleet distribution (see Chester et al. 1994). Onboard observers documented trawl captures of 83 sea turtles. Most were loggerhead sea turtles (*Caretta caretta*) but an appreciable incidence (35%) of the endangered species Kemp's ridley *Lepidochelys kempi*) was also noted.

Early in the season (Nov-Dec) sea turtle catch rates were greater south of Cape Hatteras in waters <20 meters deep and >15°C. Much of the fleet activity was in the near shore zone by smaller vessels (rerigged shrimpers). However, during the whole study period active sea turtles were observed even north of Cape Hatteras in waters as cold as 10°C. Aerial surveys revealed that sea turtles were more abundant in warmer waters but animals occurred over a wide range of SST, particularly in early winter. As the coastal waters cooled later in the winter, sea turtles tended to occur more often in proximity to temperature frontal boundaries. Gulf Stream eddies warm the shelf waters south of Cape Hatteras and turtles may remain there all winter but late in the season the summer flounder move offshore and the trawl fleet is out of the area. This reduces the opportunity for sea turtle-flounder fishery interactions.

Episodically, strong sustained northerly winds push the colder Mid-Atlantic coastal waters southward along the North Carolina coast to Cape Hatteras and beyond. At times, this cold water may penetrate south to Cape Lookout, NC as it did in late January 1992 (see Fig. 1 in Chester et al. 1994). Sea turtles tend to leave cold water areas and occur either south of Cape Hatteras or along the frontal zones whose locations are mediated by the Gulf Stream and persistence of northerly wind. By mid-January, the shelf waters generally reach 10°C or less as far south as Cape Hatteras , but cold waters may move north or south of the Cape, driven by weather systems. We observed sea turtles in much colder water than that formerly attributed as a limit to active feeding distribution, 15 °C (Lutz and Dunbar-Cooper 1984). Aerial as well at sea observer sightings of sea turtles declined as temperatures declined, with only rare encounters below 11°C.

The dynamics of water masses near Cape Hatteras suggest that SST imagery from CoastWatch could serve as a monitoring and predictive tool. NMFS sought to develop the spatial and temporal understanding of the sea turtle and flounder fishery which would minimize the fishery interactions with these threatened and endangered species during the winter trawl fishery for summer flounder off Virginia and North Carolina. The principal environmental condition determining risk to sea turtles were water temperatures of 11°C or higher since sea turtles were rare or absent at temperatures below 11°C. NMFS used the SST imagery for shelf water off Virginia and North Carolina as available between November and January in 1992-95 to determine the need (potential risk to sea turtles) to enact emergency or interim rules for sea turtle conservation as provided under the Endangered Species Act. The November-December period was the time of highest risk for fishery interactions. Coincidentally, since October 1993, turtle excluder devices (TEDs) have been required in summer flounder trawls used in the area bounded by 37° 05' North (Cape Charles, VA) and 33° 35' North (NC-SC border). These TEDs were designed, developed, and tested in the flounder fishery during 1992 and 1993 because of the observed encounter rates, long tow times commonly used in the flounder fishery (modally ~3 hr) and water temperatures conducive to turtle presence on the fishing grounds. Using the SST imagery each fall-winter, NMFS has been able to monitor the location of winter temperatures <11°C in the flounder TED zone. When requested by industry and stable water temperatures (<11°C) persisted south to Cape Hatteras, NMFS Southeast Regional Director has been able to move the TED line south from Cape Charles, VA to Oregon Inlet, NC. This provides protection to the sea turtles and allows a flexible zone where use of TEDs in flounder trawls is required. Several years of SST monitoring experience and risk determination lead to NMFS publishing a Final Rule on January 24, 1996 that established a flounder TED requirement and a seasonal area of exception. Flounder TEDs will not be required in the area between Cape Charles, VA and Oregon Inlet, NC between 15 January and 15 March, unless monitoring of water temperatures by NMFS indicates that sea turtles are likely to be in the area (SST > 11°C). CoastWatch SST imagery is the primary data reviewed by NMFS in making an annual evaluation of the flounder TED line. The described system of NOAA environmental satellite derived data and summer flounder fishery monitoring is now codified in Federal regulations. It represents the first case, to our knowledge, of a required, direct use of NOAA's CoastWatch SST data in active fishery management and protection of sea turtles.

III. Tomorrow - Introduction

Phytoplankton blooms are closely coupled to physical processes. Increased access to archived wind, sea surface temperature and ocean color data sets aids in retrospective analyses of bloom events and provides vital linkages of physical and biological processes. From such analyses conceptual models of bloom initiation, transport, maintenance and dissipation may help identify the timing of bloom initiation and define environmental conditions conducive to cell growth. The advent of online, real time environmental data, new ocean color sensors and hyperspectral scanners may allow enough predictive capability so that harmful or toxic bloom conditions can be detected, research efforts focused and reliable information provided to the resource users and managers, before effects of these blooms are manifest in near shore areas.

The physical, physiological and behavioral characteristics of phytoplankton bloom species affect their detection by remote sensing methods. Detection is based on the differential absorption and backscatter of irradiance; certain species are more amenable to detection because of the optical characteristics of the cells themselves (Millie and Schofield 1995). Surface blooms of coccolithophores with external calcium carbonate plates, diatoms with silica frustules or spines and cyanobacteria with highly reflective gas vacuoles, form extensive patches that are highly reflective and readily detected on visible-band images collected by the CZCS (Coastal Zone Color Scanner) on Nimbus-7, the Landsat MSS (Multispectral Scanner) series and the AVHRR on NOAA polar orbiting weather satellites (Ackelson et al. 1988; Balch et al. 1991; Kahru et al. 1994; Subramaniam and Carpenter 1994). Monospecific blooms of large, phototactically positive cells with numerous chloroplasts provide a strong signal and may be detected by ocean color sensors at cell concentrations 10 to 100 fold less than are required for visual detection of "discolored water" (Tester et al. 1997). Dense blooms may also absorb enough energy to increase the water temperature by >1°C and be seen as a warm "patch" in thermal imagery (Kahru et al. 1993). Development of phytoplankton group-specific algorithms has used a variety of approaches, including color thresholds with CZCS detection of anomolous brightness features and AVHRR. This has been most successful in defined situations employing high resolution multispectral scanners and detailed pigment analyses (Millie et al. 1992; Sakshaug et al. 1991).

Equally important to detection of phytoplankton blooms by remote sensing is the spectral quality, thermal signature and hydrographic features of the waters surrounding a bloom. Frequently blooms are found along frontal zones and these hydrographic features may be coherent over scales of 10^2-10^3 km. The physical and biological processes affecting bloom dimensions are critical because resolution of patches <10-100 km^2 is not generally possible. Major current systems (Gulf Stream, Kuroshio Current) are frequently implicated in the transport of blooms and these currents can be tracked most simply and reliably using thermal AVHRR imagery (Satsuki et al. 1989; Tester et al. 1991). Blooms occurring in optically clear, offshore waters are more easily detected and interpreted, however algorithm corrections developed for AVHRR, CZCS and Landsat TM data from turbid systems have made bloom detection in coastal or estuarine environments possible (Ekstrand 1992; Stumpf and Tyler 1988; Tyler and Stumpf 1989).

A conceptual model of species specific bloom dynamics is valuable in understanding conditions conducive to bloom initiation and development. If one or several of the environmental cues necessary for bloom initiation, development or transport are detectable via remote sensing techniques they can serve as important signals for early warning of harmful algal blooms (HABS)(Tester and Steidinger 1997). Local bloom development may be characterized by differential stratification of the water column, weak tidal currents and low wind speeds. Transport of blooms is associated with strengthening and persistence of wind conditions, upwelling-downwelling events or entrainment into fronts or currents. Bloom dispersal results from mixing and flow divergence. For more specific information about harmful algal blooms in US waters, their ecology and oceanography (ECOHAB 1995) see the following web site: **http:/habserve1.whoi.edu/hab/ nationplan/ECOHAB/ECOHABhtml.html**

III. Tomorrow: Methods

A. AVHRR - One of the most popular instruments for the oceanographic community is the Advanced Very High Resolution Radiometer (AVHRR) that provides sea surface temperature (SST) imagery. Satellite SSTs are made by converting the radiance measured in the infrared channels to brightness temperatures and using multiple bands together with *in situ* measurements to correct for atmospheric water vapor to establish the SST. The SST algorithms are accurate to <1°C in cloud free conditions, without need for local calibrations. This sensor onboard polar orbiting environmental satellites (POES), better known as weather satellites, has been observing the earth since the first launch of TIROS 1 in 1960. The current series of satellites began with the launch of TIROS-N (Advanced Television Infrared Observation Satellite) in 1978. The US operates two satellites simultaneously, with each of these circling the globe 14 times per day. The POES satellites continuously collect information from a 2500 mile wide strip of earth below, progressing westward on successive orbits and provide two complete pictures of the earth every day from each satellite. Continuous synoptic coverage appropriate to feature tracking with a pixel resolution of 1.0-1.4 km is provided.

B. OCEAN COLOR - Coastal Zone Color Scanner flown on Nimbus-7 from November 1978 to mid-1986 was specifically designed to observe ocean color and make quantitative measurements of oceanic radiance (443nm, 520 nm, 550 nm, 670nm, 750 nm). Phytoplankton pigment (chlorophyll) concentration in surface waters can be related to ocean color either empirically, using oceanic observations, or theoretically by using the theory of radiative transfer in sunlit waters to estimate phytoplankton biomass and primary productivity over large regions (Behrenfeld and Falkowski 1997; Gregg and Walsh 1992). It is one of the most valuable and extensively used data sets available to the oceanographic community; the CZCS images can be viewed and data ordered via the following web site: **http://daac.gsfc.nasa.gov**

After more than a decade without ocean color imagery, the Ocean Color and Temperature Sensor was launched in 1997 but unfortunately was operational for only a few months before debris struck its solar panel and rendered it inoperative. The long awaited NASA's SeaWiFS (Sea-Viewing Wide Field-of-View) sensor was launched by NASA on 1 August 1997 and should prove to be even more sensitive than its predecessor. The latest information regarding SeaWiFS can be found at: **http//seawifs.gsfc.nasa.gov/SEAWIFS.html**

C. LANDSAT (land-observing satellites) were designed to view scenes with a wide range of brightness so their multispectral scanners lack the radiometric sensitivity to observe the subtle variations in the hue of the oceans, however strong signals indicate the distribution of riverborne sediments and phytoplankton, (Stewart 1985). Its high resolution (<80 m for multi-spectral scanner (MSS) launched in 1972) has led some researchers to examine Landsat images for information on thermal effects, (Daby 1994) suspended sediment concentrations and chlorophyll a (Garcia and Robinson 1991; Tassan 1993).

D. RADAR SAT - Synthetic aperture radar (SAR) satellite earth observation techniques represent a new tool to detect ocean features independent of light and weather conditions (see Staples et al. 1997). RADAR SAT-1 launched 4 November 1995 has variable field of view (depending on beam mode, incidence angle) from 8x8m to 100x100m and may prove most valuable when other sensors are limited by ambient weather conditions.

E. LIDAR - The multispectral scanner, a multi-wavelength instrument with >250 band widths can be flown in a conventional aircraft or in a simpler version, suspended from a buoy to characterize the spectral quality of the water. Species-specific algorithms are particularly useful when toxic species (flagellates) distinguished from non-toxic (diatoms) (Sakshaug et al. 1991) and the results combined with pigment analyses for confirmation (Millie et al. 1992).

VI. Tomorrow: Results & Discussion

For remote sensing detection of harmful algal blooms, sea surface temperature (AVHRR) imagery has been used to study the bloom dynamics of *Alexandrium tamarense* and the onset of paralytic shellfish poisoning in the southwest Gulf of Maine (see Keafer and Anderson 1993). Comparative imagery from 1989-1991 detected a warm coastal current that formed from spring runoff and served to transport *A. tamarense* cells south along the New England coast. Coastal upwelling was detected in two years of a three year study and it caused the warm, buoyant plume containing *A.*

tamaranse cells to move offshore and away from nearshore shellfish beds. The thermal imagery was valuable in helping understand the short-term oceanographic processes responsible for the development and behavior of the plume and the subsequent distribution of *A. tamarense* cells. The thermal features associated with spring runoff, a low density coastal plume and regional upwelling have predictive power in that they can be monitored to detect conditions conducive to *A. tamarense* bloom initiation and transport.

Gymnodinium breve blooms are common along the west coast of Florida and have been recorded there in 21 of the last 22 years. The onset of these blooms, in association with the onshore movement of the (Gulf) Loop Current, has been noted (Tester and Steidinger 1997). However, this had never been quite so dramatically demonstrated until February 1996 when a thermal feature (AVHRR 14 Feb 1996; see Stumpf et al. 1997) transported *G. breve* cells into Florida coastal waters. More than 150 endangered manatees died from exposure to brevetoxins between 1 March and 1 May 1996 (Landsberg and Steidinger 1997).

Another red tide bloom event was the product of transport of *G. breve* cells by the Gulf Stream (see Tester et al. 1991; Tester and Steidinger 1997). About 30 days after a red tide bloom near Charlotte Harbor-Sarasota, FL, satellite images of sea-surface temperature (AVHRR) substantiated the shoreward movement of a filament of Gulf Stream water onto the narrow continental shelf between Cape Hatteras and Cape Lookout, NC. This filament was a source of *G. breve* cells. It remained in nearshore waters and was identifiable in satellite images for >19 days. This was the first recorded occurrence of *G. breve* north of Florida and represented a range extension of >800 km. During the bloom that followed, shellfish beds were closed for the next 4-6 months, causing an estimated $25 million loss to fisheries and tourism.

NOAA's polar orbiting satellites were able to detect an ocean thermal feature associated with the event. These sea surface temperature (AVHRR) images provided a means for understanding the oceanographic mechanisms responsible for the occurrence and distribution of some toxic phytoplankton species. The imagery has since been used for a variety of marine research, management and educational purposes and is now available for all US coastal waters including those of Alaska, Hawaii and the Great Lakes. The CoastWatch web address is **htttp://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/CW/coastwatch.html**

Further, the Coastal Services Center, Charleston has an experimental project, designed as a "proof of concept", that will attempt to forecast *G. breve* blooms for the west Florida shelf using a combination of satellite imagery and meteorological data (Coastal Remote Sensing Program 1997). If the project is implemented it will be a major milestone in the efforts to forewarn coastal residents, researchers and marine resource managers about the occurrence and distribution of harmful algal blooms (Boesch et al. 1996).

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